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A COMPUTER ANALYSIS OF TWO-STAGE HYPERVELOCITY MODEL LAUNCHERS

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UNITED STATES NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

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Ballistics Research Report 67

COMPUTER ANALYSIS OF TWO-STAGE HYPERVELOCITY MODEL LAUNCHERS

Prepared by:
R. Piacesi, D. F. Gates, and A. E. Seigel

ABSTRACT: A computer study for predicting high-speed launcher performance was conducted using a one-dimensional hydrodynamics computer code. This computer code uses the Lagrangian scheme, and is based on the "q" method as devised by Von Neumann and Richtmyer. These calculations provide understanding for the proper variation of the launcher parameters for optimization of launcher performance. A series of calculations for the 2-in. Two-Stage Hypervelocity Model Launcher, which is in use in the NOL 1,000-ft. Hyperballistics Range No. 4, are presented and are compared with the actual performance of the launcher.

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COMPUTER ANALYSIS OF TWO-STAGE HYPERVELOCITY MODEL LAUNCHERS

This report constitutes a basic study of performance of two-stage hypervelocity model launchers. The results will be applied to the operation of the model launchers existing in the ranges at the Naval Ordnance Laboratory.

This work was sponsored by the Re-Entry Body Section of the Special Projects Office, Bureau of Naval Weapons, under the Applied Research Program in Aeroballistics under Task Number NOL-364.

R. E. ODENING
Captain, USN
Commander

R. Kenneth Lobb

R. KENNETH LOBB
By direction

CONTENTS

ILLUSTRATIONS

TABLES

LIST OF SYMBOLS

A	Cross-sectional area
E	Specific internal energy
M	Mass
V	Specific volume
C_o	Constant used to specify the thickness of the shock region
j	Mass point number
n	Cycle number
p	Pressure
q	Artificial viscosity
t	Time
u	Velocity
x	Eulerian position
ρ	Density

INTRODUCTION

To make possible the study of hypervelocity phenomena in the laboratory, two-stage hypervelocity model launchers have been developed to propel projectiles at velocities presently as high as 34,000 feet per second (this velocity has been achieved at the NASA Laboratory at Ames). Due to the multiple number of phenomena occurring in a two-stage launcher, it becomes very difficult to predict launching velocities and virtually impossible to determine how to vary the launcher parameters to maximize the velocity capability of the launcher. Maximizing the velocity capability while maintaining a moderate pressure behind the projectile is particularly difficult; this has been a problem of interest for the Naval Ordnance Laboratory Launchers which have been used to launch scale models that cannot withstand high accelerations. To overcome the tediousness of hand calculations and the inaccuracies of approximate analyses (see for example, ref. (1)), calculations of the performance of a two-stage model launcher were done numerically by the authors, utilizing an IBM 7090 computer. The method of calculation and some results are described below.

DESCRIPTION OF THE COMPUTER CODE

The computer code is a one-dimensional hydrodynamic program, using the Lagrangian scheme, and is based on the "q" method as devised by Von Neumann and Richtmyer (refs. (2) and (3)). The code solves quasi-one-dimensional hydrodynamic problems, i.e., it will handle cases of one-dimensional flow through ducts of varying cross section. Automatic treatment of the shock by the "q" method lends itself nicely to the solution of multiple shock systems such as occur in the two-stage light-gas launchers.

The computer program, which is written in FORTRAN for the IBM 704 and 7090 computers (refs. (4) and (5)), is a modification of a program prepared by W. A. Walker of the Explosion Dynamics Division of the Naval Ordnance Laboratory. The code is similar, in many respects, to an earlier non-FORTRAN program obtained from the Lawrence Radiation Laboratory, Livermore, California, in 1957.

In the Lagrangian scheme the system is divided into regions, each having its own equation of state,* and each region being further subdivided into zones. Mass points containing one-half the mass of each of two adjacent zones are assumed at the interface of these two zones. These mass points are labeled initially (see fig. 1) and carry these labels throughout the entire computation. The hydrodynamic equations of motion

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* The equation of state may be that of solids, liquids or ideal and non-ideal gases.

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and conservation of energy are put into finite difference form. These, along with a suitable stability calculation, are then solved numerically to determine the subsequent motion of these weighted interfaces.

Initial values of the internal energy E_o, the density ρ_o, the specific volume V_o, the pressure p_o and the velocity u_o are given for each zone. The new values of these variables and the new positions of the mass points are calculated by numerically integrating the hydrodynamic equations. An appropriate variable time increment is calculated for the numerical integration at each computation cycle to assure stability of the finite difference equations. At each time step, the pressure differential at each interface is used in the equation of motion to determine the acceleration of the mass points. Using the accelerations, the new velocities are computed. Knowing the position of its interfaces, the volume of a zone is computed. The pressure and internal energy are then obtained by a single iteration of the equation of state and the energy equation. In this manner the scheme provides a complete history of the position and velocity of the mass points and of the volume, pressure, and internal energy of the zones.

The code uses the following hydrodynamic equations:

Energy equation for isentropic flow

$$\frac{\partial E}{\partial t} = - p \frac{\partial V}{\partial t} \tag{1}$$

Equation of state

$$p = p(E, V) \tag{2}$$

Equation of motion

$$\frac{\partial u}{\partial t} = - \frac{\partial p}{\partial M} \cdot A(x) \tag{3}$$

where M, the mass, is defined in the equation

$$M = \int^{X} \rho(x) A(x)\, dX \tag{4}$$

In the "q" method, equations (1) and (3) are rewritten as:

$$\frac{\partial E}{\partial t} = -(p+q)\ \frac{\partial V}{\partial t} \tag{5}$$

$$\frac{\partial u}{\partial t} = -\frac{\partial(p+q)}{\partial X}\cdot\frac{1}{M}\cdot A(x) \tag{6}$$

where

$$q = \begin{cases} \dfrac{C_o^2}{V}\left(\dfrac{\partial u}{\partial j}\right)^2, & \dfrac{\partial u}{\partial j} < 0 \quad (7) \\ 0, & \dfrac{\partial u}{\partial j} \geq 0 \quad (8) \end{cases}$$

The term q, which is added to the pressure in equations (5) and (6), acts as an artificial dissipative mechanism giving the correct entropy change across the shock and allows the hydrodynamic variables to be continuous across the shock front. C_o is a constant which can be adjusted to spread the shock over a desired number of zones.

Equations (5), (6), (7), and (8) appear below in differenced form along with the other necessary equations in logical sequence as used in the program

$$\left(\frac{\partial u}{\partial t}\right)^n = \frac{\left(p^n_{j-\frac{1}{2}} + q^{n-\frac{1}{2}}_{j-\frac{1}{2}}\right) - \left(p^n_{j+\frac{1}{2}} + q^{n-\frac{1}{2}}_{j+\frac{1}{2}}\right)}{\frac{1}{2}\left(\Delta M_{j-\frac{1}{2}} + \Delta M_{j+\frac{1}{2}}\right)}\cdot A(x) \tag{9}$$

$$u_j^{n+\frac{1}{2}} = u_j^{n-\frac{1}{2}} + \left(\frac{\partial u}{\partial t}\right)_j^n \cdot \Delta t^n \tag{10}$$

$$X_j^{n+1} = X_j^{n} + u_j^{n+\frac{1}{2}} \cdot \Delta t^{n+\frac{1}{2}} \qquad (11)$$

$$V_{j+\frac{1}{2}}^{n+1} = \frac{\rho_{o\,j+\frac{1}{2}}}{\Delta M_{j+\frac{1}{2}}} \int_{X_j^{n+1}}^{X_{j+1}^{n+1}} A(x)_j^{n+1}\, dx \qquad (12)$$

$$q = \begin{cases} \dfrac{2c_o^2\, \rho_{o\,j+\frac{1}{2}}}{V_{j+\frac{1}{2}}^{n} + V_{j+\frac{1}{2}}^{n+1}} \left[u_{j+1}^{n+\frac{1}{2}} - u_j^{n+\frac{1}{2}} \right]^2, & u_{j+1}^{n+\frac{1}{2}} < u_j^{n+\frac{1}{2}} \qquad (13) \\ 0, & u_{j+1}^{n+\frac{1}{2}} \geq u_j^{n+\frac{1}{2}} \qquad (14) \end{cases}$$

$$\epsilon_{j+1}^{n+1} = \epsilon_j^{n} - \left[\frac{p_{j+\frac{1}{2}}^{n+1} + p_{j+\frac{1}{2}}^{n}}{2} + q_{j+\frac{1}{2}}^{n+\frac{1}{2}} \right] \left[V_{j+\frac{1}{2}}^{n+1} - V_{j+\frac{1}{2}}^{n} \right] \qquad (15)$$

$$p_{j+\frac{1}{2}}^{n} = p\left(\epsilon_{j+\frac{1}{2}}^{n+1}, V_{j+\frac{1}{2}}^{n+1} \right) \qquad (16)$$

$j = 1, 2, 3$ --- J_{max}
$n = 0, 1, 2$
$\Delta t^{n+1/2} = t^{n+1} - t^{n}$
$\Delta t^{n} = (t^{n+1/2} + t^{n-1/2})/2$
$\Delta M_{j+1/2}$ = zone mass
$A(X)^n_j$ = cross-sectional area at X

Here j refers to the mass point number and n the time cycle number.

TWO-STAGE GUN PROCESS

It is known that for an isentropically expanding gas (ideal) pushing a projectile, the pressure drop behind the projectile may be decreased by using a propellant gas with a high initial sound speed, a_o, and a low specific heat ratio γ. Since γ for gases does not differ widely, much effort is given to obtain a high initial sound speed for the driver gas.

One method of obtaining a high sound speed driver is the two-stage gun. The events occurring in the operation of a two-stage gun can be described in the following way.

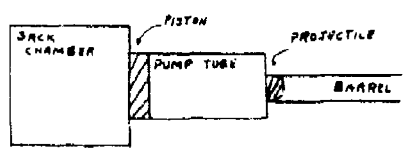

Fig. A

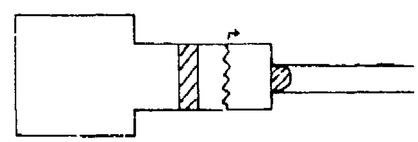

Fig. B

The back chamber contains a propellant which is burned to a high pressure. The front chamber or "pump tube" contains a low-molecular-weight gas such as hydrogen or helium initially at a much lower pressure than the peak pressure of the back chamber gas (fig. A). The diaphragm separating the back and front chambers is opened near the back chamber peak pressure, causing the piston to be accelerated. A shock precedes the piston down the pump tube which reflects between the piston and the end of the pump tube several times, raising the temperature and pressure of the light gas (fig. B). The resulting high temperature, along with the low molecular weight of the gas produces a much higher sound speed for the pump tube gas than was possible to attain for the back chamber driver.

Although the drop in pressure behind a projectile may be decreased by increasing the sound speed in the driver gas, the increase in sound speed practically attainable is insufficient in itself to maintain the pressure at the desired constant value.

What is required is that the reservoir pressure in the pump tube be increased during the movement of the projectile. By so doing the tendency of the pressure behind the projectile to drop is overcome. The higher the sound speed of the driver gas, the less is the required reservoir pressure increase to maintain the pressure behind the projectile constant. In practice the reservoir pressure would be required to rise perhaps a factor of 10 or more times the value of the pressure behind the projectile to maintain it constant.

The two-stage gun provides the possibility of increasing the reservoir pressure in the pump tube by means of the piston in the pump tube which, by its movement, compresses the reservoir gas, thus effecting the required increase of pressure.

Therefore, the condition desired in the two-stage gun is a constant pressure behind the projectile as a result of the proper increase of pump tube reservoir pressure. The selection of the variables required to attain this condition is almost impossible by means of hand calculations. The electronic computing machine offers a means for selection of the required parameters.

The processes occurring in the two-stage gun are readily seen in the plots of information as obtained from the electronic computer. Figure 2 is a typical calculated distance-time plot showing the trajectories of shocks between the piston and projectile, the piston trajectory, and the projectile trajectory. Figure 3 is a plot of calculated pressure behind the model as a function of distance along the barrel. Figure 4 is a calculated velocity-time plot of the projectile and shows clearly the effect of shock impingements on the back of the model.

CALCULATIONS AND RESULTS

Many calculations were made to determine optimum gun operating conditions for various NOL Hypervelocity Facilities. As mentioned above, the problem of optimum performance is complex due to the number of parameters involved. For a given gun geometry these parameters are the initial back-chamber conditions, the initial front-chamber conditions, the weight of the piston, the weight of the projectile and the projectile release pressure. There are certain physical restrictions existing on the facility and the projectile; these being, a limiting pressure that the gun can contain without damage being done, and a maximum acceleration that the projectile can withstand without breaking up. In addition, it may be desired to vary the gun geometry itself (length and diameter of launch tube, etc.) to obtain an optimum model launcher. By adjusting the above parameters, keeping in mind the physical limitations, optimum operating conditions can be determined.

A typical set of computer calculated results for the 2-in. Two-Stage Hypervelocity Model Launcher, which is in use in the NOL 1,000-ft. Hyperballistics Range No. 4, are shown in Tables 1, 2, and 3. Figure 5 shows the dimensions of the 2-in. two-stage facility. A large portion of the success of this facility in presently firing saboted models of various aerodynamic configurations over 17,000 feet per second is attributed to these calculations (ref. (6)). Figure 6 is a photograph of the type of cone model fired in the range at velocities exceeding 17,000 feet per second. The computer calculation showed that the highest pressure the projectile would feel was 25,000 psi. Figure 7 is a photograph of a more blunt-nosed model in flight. This type has been launched successfully at 20,000 feet per second in another of the NOL Ballistics Ranges for which calculations had been made.

The calculations assume the back-chamber propellant is preburned and is an ideal gas with a constant specific heat ratio γ. A constant γ is also used for the pump tube gas. Co-volume effects in the pump tube gas were taken into account for the 2-in. two-stage calculations.*

The calculations for the 2-in. two-stage launcher for the higher velocity cases ($>$ 15,000 feet per second) predict higher velocities (about 10 percent higher) than are obtained experimentally. Figure 8 shows a comparison of the theoretical calculations and the experimental results.** For smaller bore launchers the deviation appears more serious. This is not disturbing in that one is still guided in the direction to vary the parameters for optimizing the performance. The difference in predicted velocities and experimental velocities is attributed largely to frictional effects. The frictional effects can be accounted for, but only at the expense of computer time which is costly. When optimum conditions are obtained, losses due to friction can be taken into account for that set of conditions (ref. (7)).

CONCLUSION

Two-stage gun performance calculations were made using a one-dimensional hydrodynamics computer code. This code takes

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* As noted before, any equation of state may be used for the gas.

** The experimental firings were made with the barrel evacuated.

account of the gas dynamic processes occurring including the shocks which are reflected back and forth both in the pump tube and in the barrel. The true equations of state are used for the gases as well as for the piston and projectile. Although the code is one-dimensional, it had been previously demonstrated experimentally that the one-dimensional approximation is excellent for unsteady flows between tubes of different diameters (ref. (8)). Friction effects can also be taken into account in this code.

Predictions by approximate methods of computations for the pressure experienced by the model have been found to be in error by a factor which may be as high as 4 since the sharp pressure peaks which occur are not accounted for by these approximate methods. Without the computer code it becomes virtually impossible to select conditions for launching fragile models (such as the cone shown in fig. 6) at relatively high velocities without failure of the model. A common experience in attempting to launch such a small angle cone in ballistic range facilities is the emergence of the cone with the nose tip broken off (spalled). On the basis of the experience gained with the NOL Two-Stage Launchers, it is felt that successful launching of fragile models at high velocities can only be achieved without the necessity for many trials with a computer program of this type which accurately calculates the conditions occurring during the firing.

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TABLE 1

COMPUTER PERFORMANCE CALCULATIONS FOR 240-GRAM PROJECTILE

Back Chamber Pressure (psi)	Pump Tube Pressure (psi H_2)	Piston Weight (gm)	Projectile Release Pressure (psi)	Pressure Felt By Projectile (psi)	Maximum Pressure In Taper (psi)	Velocity 240 Calibers (ft/sec)
20,000	750	5,540	5,000	82,000	125,000	18,200
20,000	500	5,540	5,000	175,000	195,000	18,730*
20,000	750	1,000	5,000	116,900	118,600	14,600
20,000	750	2,700	5,000	91,350	121,200	17,400*
20,000	750	5,540	5,000	82,000	125,000	18,200
20,000	750	9,000	5,000	91,840	123,650	18,500
20,000	1,000	1,000	5,000	111,900	122,900	13,900
20,000	1,000	5,000	5,000	63,000	107,300	17,350
20,000	1,000	9,000	5,000	64,600	112,300	17,600
20,000	1,500	1,000	5,000	61,500	82,600	12,650
20,000	1,500	5,000	5,000	59,450	78,900	15,200
20,000	1,500	9,000	5,000	29,800	81,400	15,000
30,000	1,500	9,000	5,000	69,300	155,700	19,200
30,000	2,000	9,000	5,000	52,000	129,200	17,200
30,000	1,500	18,000	10,000	53,700	128,000	18,500
30,000	2,000	18,000	10,000	42,700	112,500	17,100
30,000	2,000	18,000	5,000	32,000	115,350	14,900
40,000	2,000	2,000	5,000	107,500	136,700	17,400
40,000	1,500	9,000	5,000	114,000	246,500	23,650
40,000	2,500	9,000	5,000	76,400	173,600	18,700

* (200 Cal.)
Initial pump tube temperature 300°K

TABLE 2

COMPUTER PERFORMANCE CALCULATIONS FOR 120-GRAM PROJECTILE

Back Chamber Pressure (psi)	Pump Tube Pressure (psi H_2)	Piston Weight (gm)	Projectile Release Pressure (psi)	Pressure Felt By Projectile (psi)	Maximum Pressure In Taper (psi)	Velocity 240 Calibers (ft/sec)
20,000	100	2,000	5,000	178,000	213,000	22,800
20,000	200	9,000	5,000	63,000	125,100	20,000
20,000	300	9,000	5,000	57,300	101,200	20,600
20,000	500	2,000	5,000	87,000	121,700	22,300
20,000	500	5,000	5,000	68,000	126,300	22,000
20,000	500	9,000	5,000	56,400	121,600	20,600
20,000	750	2,000	5,000	54,250	98,200	20,400
20,000	500	18,000	5,000	21,750	64,300	17,800
30,000	500	18,000	5,000	41,600	105,800	20,700
20,000	1,000	18,000	5,000	15,600	80,600	17,100
20,000	1,000	18,000	20,000	41,800	87,400	19,300
20,000	1,000	1,000	5,000	42,000	67,900	17,500
20,000	1,000	5,000	5,000	37,700	106,700	19,900
20,000	1,000	9,000	5,000	23,000	102,500	19,500
20,000	1,500	18,000	5,000	9,300	68,000	12,600

Initial pump tube temperature 300°K

TABLE 3

COMPUTER PERFORMANCE CALCULATIONS FOR 60-GRAM PROJECTILE

Back Chamber Pressure (psi)	Pump Tube Pressure (psi H_2)	Piston Weight (gm)	Projectile Release Pressure (psi)	Pressure Felt By Projectile (psi)	Maximum Pressure In Taper (psi)	Velocity 240 Calibers (ft/sec)
20,000	100	500	5,000	49,000	72,000	25,600
20,000	100	1,000	5,000	69,600	83,000	25,700
20,000	100	9,000	20,000	90,000	122,000	23,200
20,000	300	500	5,000	76,000	101,200	25,300
20,000	300	1,000	5,000	117,700	117,700	27,000
20,000	300	9,000	5,000	35,670	95,300	24,400
20,000	500	9,000	5,000	35,200	117,700	25,200
20,000	1,000	9,000	5,000	13,600	104,000	19,700
20,000	1,000	9,000	20,000	28,700	98,300	20,900
20,000	1,500	9,000	5,000	29,000	161,700	20,100
30,000	1,500	9,000	5,000	8,700	82,600	12,600

Initial pump tube temperature 300°K

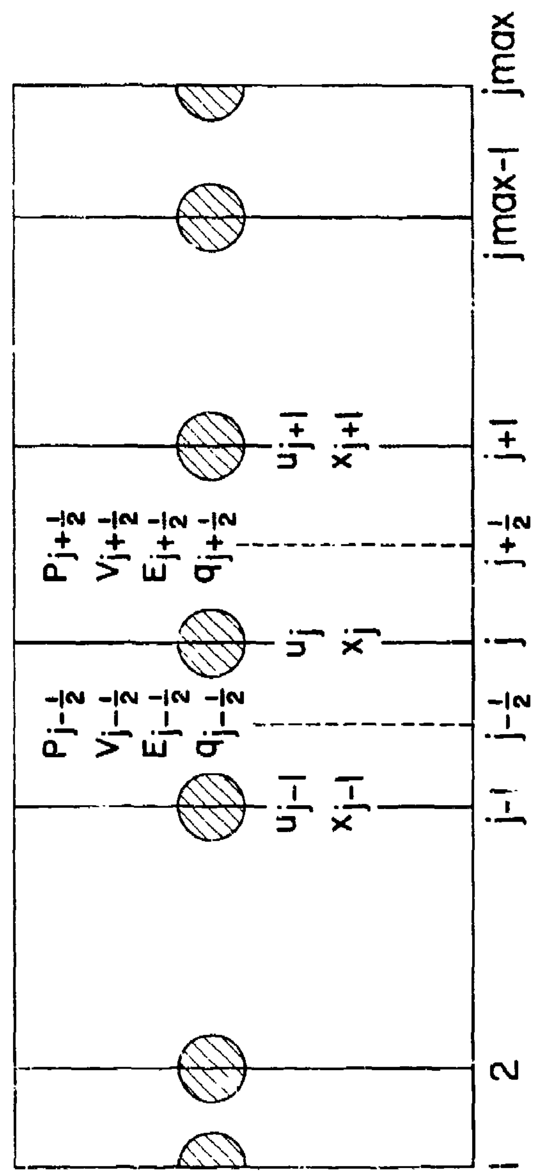

FIG. 1 THE MASS POINT MODEL.

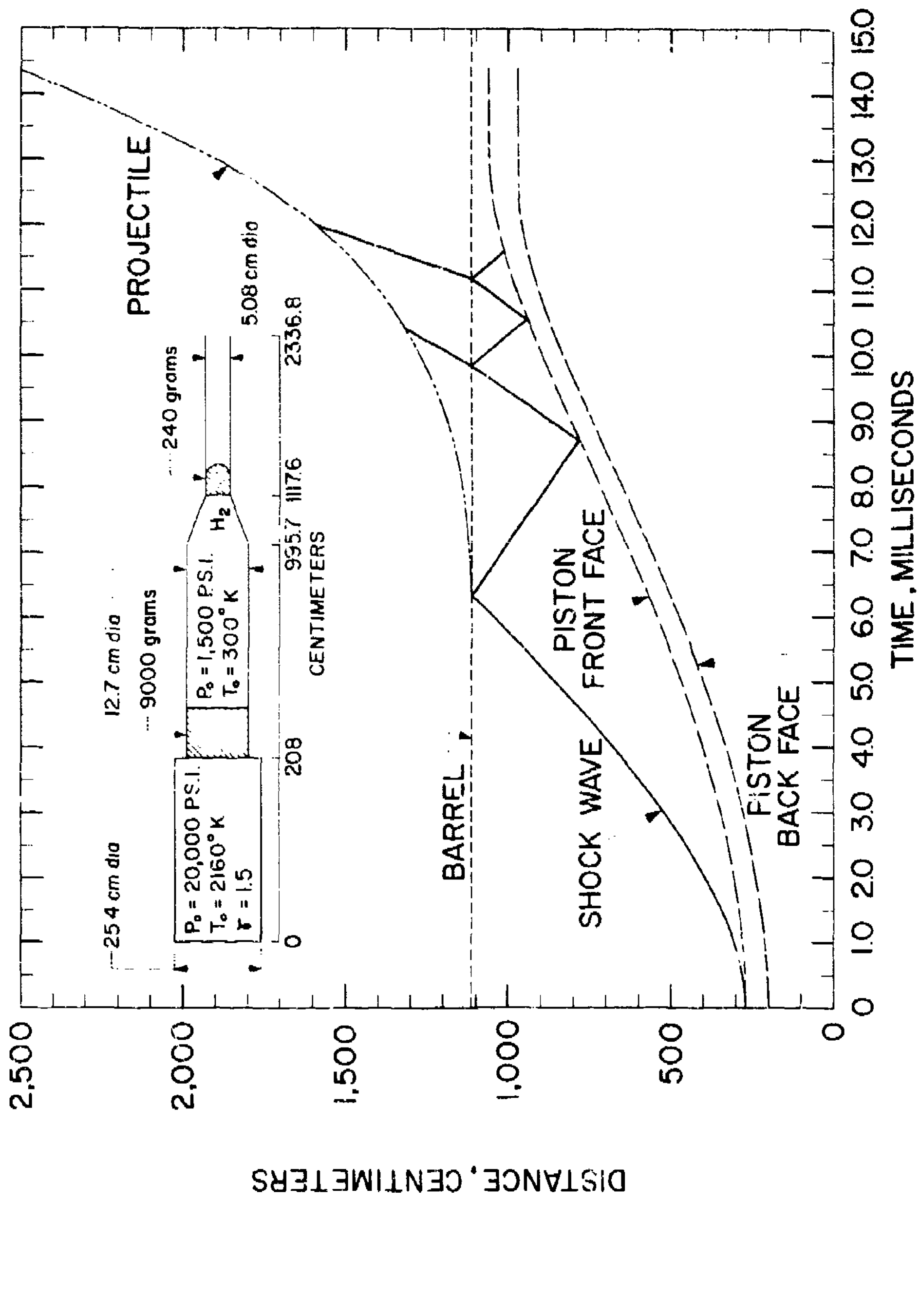

FIG. 2 TWO-STAGE GUN, TIME-DISTANCE PLOT

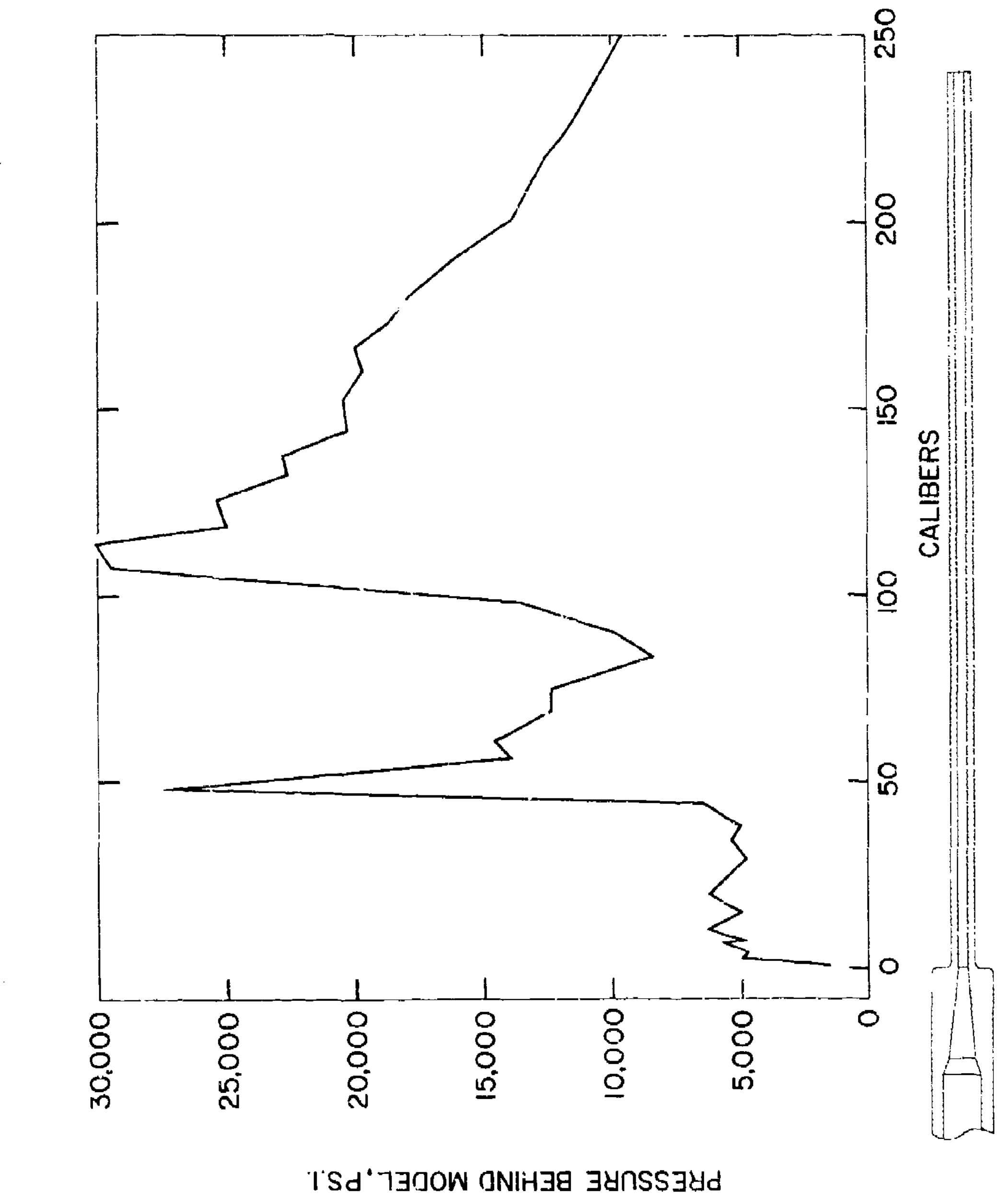

FIG.3 PRESSURE BEHIND MODEL VS BORE TRAVEL IN CALIBERS

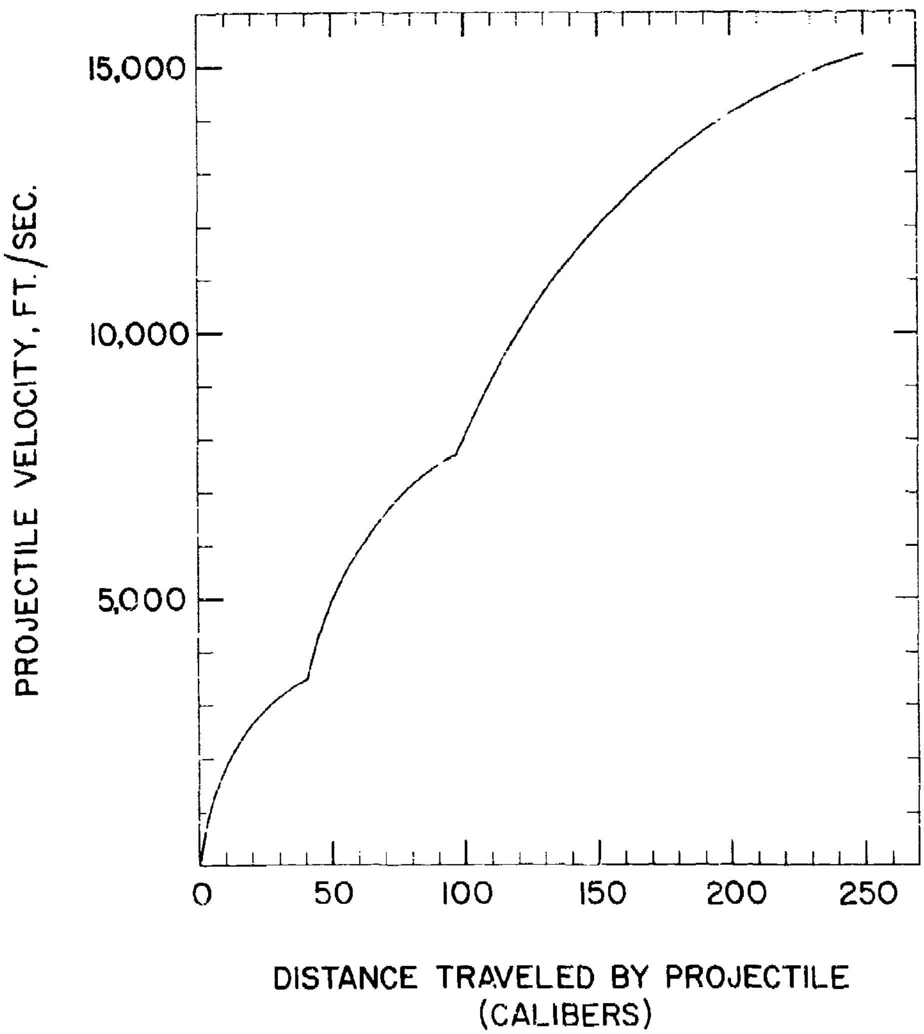

FIG.4 PROJECTILE VELOCITY VS BORE TRAVEL IN CALIBERS

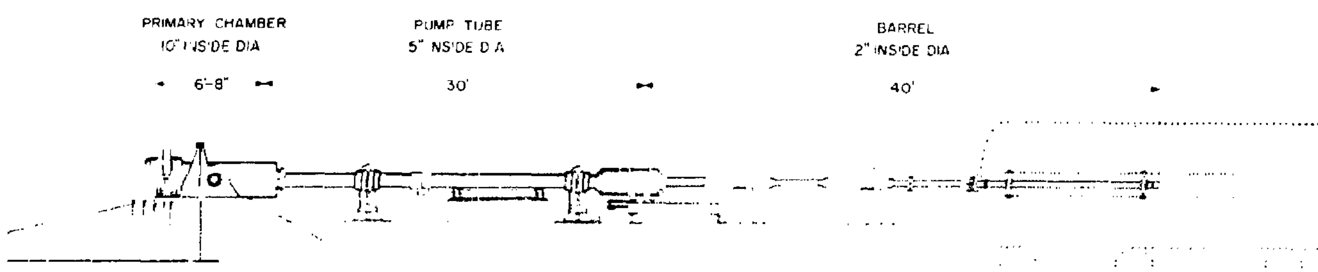

FIG. 5 TWO-INCH TWO-STAGE LIGHT GAS GUN

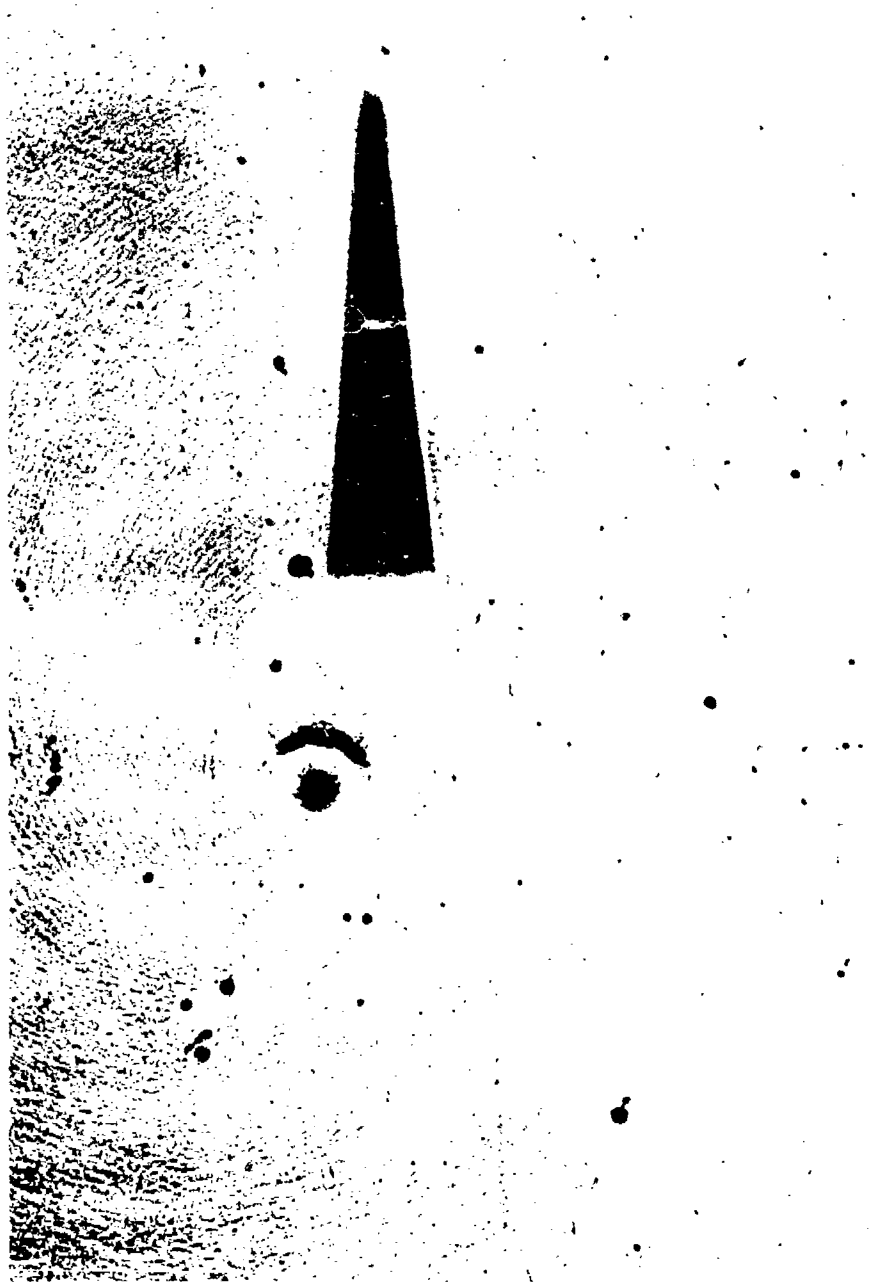

FIG. 6 10° TOTAL ANGLE CONE V=17,600 FT./SEC.

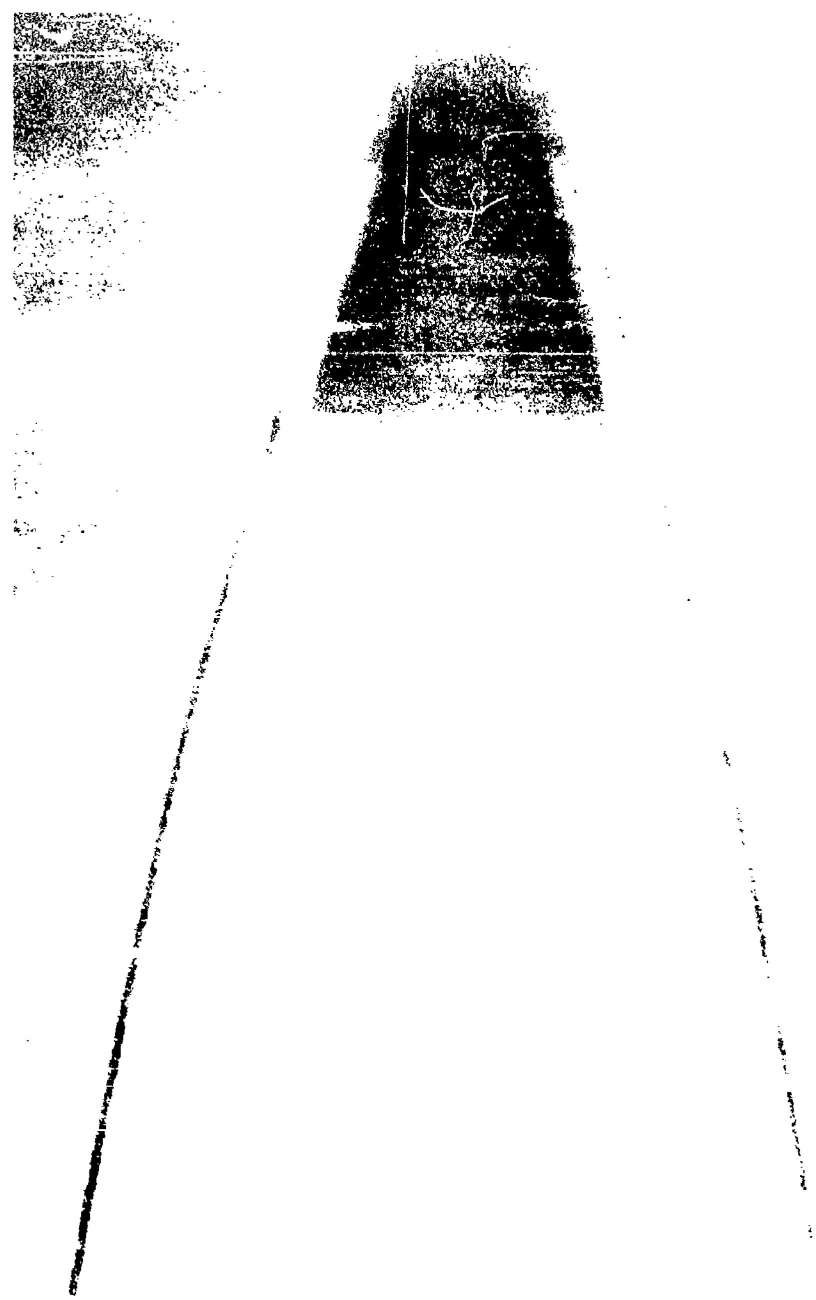

FIG. 7 BLUNT NOSED CONE LAUNCHED IN NOL FACILITY

INITIAL CONDITIONS FOR CALCULATED POINTS

POINT	BACK CHAMBER	FRONT CHAMBER H_2	PISTON WEIGHT	PROJECTILE WEIGHT
1	20,000 p.s.i.	500 p.s.i.	9000 gms.	60 gms.
2	20,000 p.s.i.	1,000 p.s.i.	9000 gms.	120 gms.
3	20,000 p.s.i.	1,500 p.s.i.	9000 gms.	240 gms.

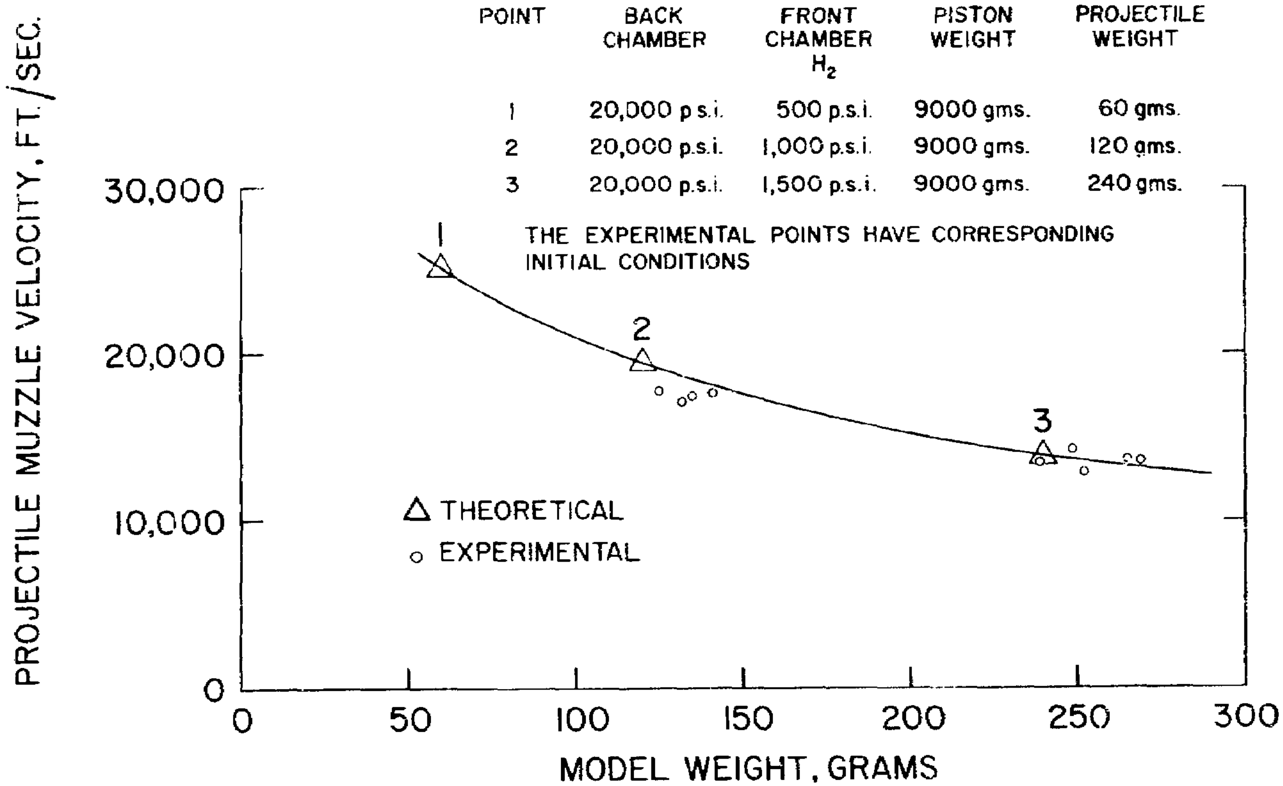

FIG. 8 COMPARISON OF THEORETICAL CALCULATIONS AND EXPERIMENTAL RESULTS FOR NOL TWO-INCH TWO-STAGE LAUNCHER

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Model	MODE	Calculation	COMA		
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Two-Stage	SECN	Parameters	PARA		
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High speed	HIGS	Inch	INCH		
Velocity	VELC	Projectile	PROJ		
One-dimensional	ONED	Gas	GASE		
Hydrodynamic	HYDN	Gun	GUNS		
Code	CODE				
Lagrangian	LAGR				

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Naval Ordnance Laboratory, White Oak, Md.
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COMPUTER ANALYSIS OF TWO-STAGE HYPERVELOCITY MODEL LAUNCHERS, by R. Piacesi and others. 20 Feb. 1963. 9p. tables. (Ballistics research report 67). NOL task 364.

UNCLASSIFIED

A computer study for predicting high-speed launcher performance was conducted using a one-dimensional hydrodynamics computer code which uses the Lagrangian scheme, and is based on the "q" method of Von Neumann and Richtmyer. These calculations provide understanding for proper variation of launcher parameters for optimization of launcher performance. A series of calculations for the 2-in. two-stage hypervelocity model launcher, in use in the NOL hyperballistics range are presented and compared with the actual performance of the launcher.

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